Enhancing Reliability in Medium Voltage Distribution Networks with Directional Fault Passage Indicators without Voltage Sensors

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***Abstract*— Fault Passage Indicators (FPI) are a cost effective solution to improve reliability and power quality indexes in distribution grids, such as SAIDI and CAIDI. Directional problems, such as the back-feed current and the connection of Distributed Generators (DG) have triggered the need of Directional FPIs. The typical method for directionality is polarization, which implies the use of Voltage Sensors. However, the costs and difficulties of installing such sensors over the Distribution Network turns the directionality into an expensive necessity. Researchers and manufacturers have come up with directional voltage sensor-less solutions that make use only of inexpensive current sensors and alternative signal processing techniques. The paper provides an exhaustive literature review about those methods and a case study over a Belgian grid where some of those algorithms are implemented and tested.**

Keywords*—Reliability; Directional Fault Passage Indicator; polarization; back-feed current; Distributed Generation; symmetrical components

I. INTRODUCTION

FPIs are little devices that sense the passage of over-current through a cable, presumably due to a grid fault. The objective of allocating these devices is to help and guide the fault locating crew to the faulted cable section, between the last tripped FPI and the first non-tripped one [1], as a standard procedure in the Fault Location, Isolation and Restoration of Supply strategy (FLISR).

Some DNOs use to locate faults by means of trial-and-error switching maneuvers. On the other hand, other DNOs have adopted FPIs in their grids. This has been reported as a cost effective solution to improve the power quality indexes related to the outage time, such as SAIDI (System Average Interruption Duration Index) or CAIDI (Customer Average Interruption Duration Index) [2]. In [3],[4], it is shown that a great reliability improvement can be achieved with a limited amount of FPIs, by estimating the associated costs and benefits of installing a net of FPIs. Often, the benefits are calculated in terms of reliability improvement and reduction of the Energy Not-Supplied (ENS), [5]. Despite the generally accepted good performance of such devices [6], most of the installed FPIs are not designed to discriminate the current flow direction and, therefore, they are sensitive to directional problems.

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The use of directional elements in the grid is not new. Directional relays are based on the polarization concept: the phase angle of the operating quantity (typically the current phasor) is compared against a reference magnitude, the polarizing quantity (normally a voltage phasor). The sustained over-current indicates the fault, whereas the angle comparison provides the direction [7], [8]. The use of such relays is mostly limited to transmission grids because of the high reliability requirements. A meshed topology that produces bidirectional power flows (during fault conditions) also requires directional elements.

In the recent times, the expansion of the distribution network and the increase of Distributed Generation have triggered the need of directionality in the MV level. These two trends have been identified as potential causes of mal-operation of non-directional FPIs.

A. Back-feed current

One type of back-feed current is shown in Fig. 1. It can be found in grids with underground, highly capacitive cables, where phase-to-ground faults are detected by means of zero-sequence over-current. The capacitive back-feed current becomes a problem when the load current is low or the fault does not produce large current, for instance in isolated grounded grids, hence, the capacitive current is not negligible. A common practice to overcome the influence of the back-feed current is to increase the pick-up zero-sequence current, therefore desensitizing it, or using directional FPIs, immune to the capacitive currents.

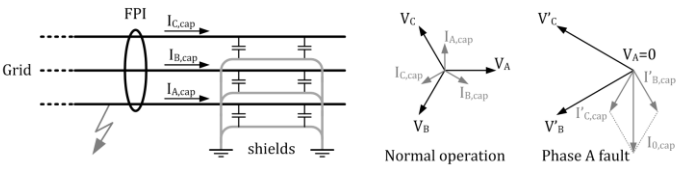

Figure 1: Zero-sequence back-feed capacitive current in shielded cables

B. Distributed Generation

The presence of DG units in the grid can have influence on the behavior of the non-directional FPIs allocated in the grid. Consider the simplified circuit of Fig. 2, where a DG unit with large short-circuit capacity is located at the end of the feeder. A fault is produced between the DG and the main grid, the DG will contribute to the short-circuit with some reverse fault current.

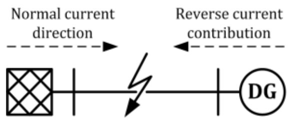

Figure 2: Reverse current contribution of a DG unit after the fault

If the contribution is large enough, the FPIs located between the fault and the DG may trip. However, several aspects need to be considered, such as the DG type, its behavior in case of short-circuit, the time to trip the anti-islanding protection, the detection algorithm or the thresholds of the FPIs.

According to the IEEE Standard 1610-2007 [9], it is recommended to allocate the FPIs in the outgoing extreme of the secondary substations, although many DNOs may allocate FPIs in both extremes. Under this recommendation, the connection of DG units with a high fault current contribution, allocated beyond the fault location may lead to directional mal-operation, as shown in Fig. 3.

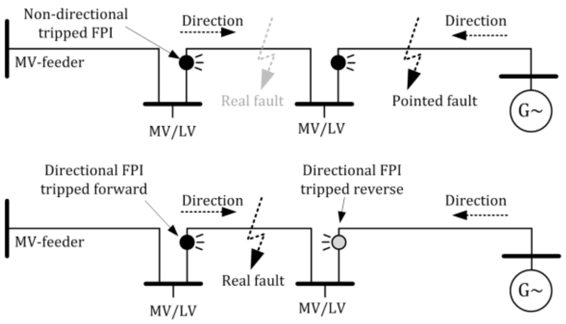

Figure 3: Directional problem due to large DG connection. Up: Mal-operation with non-directional FPIs. Down: Correct operation with directional FPIs.

The operation of the grid with automatic recloser may overcome this problem. Once the fault is cleared by the feeder circuit breaker (CB), the DG protections also trip and remain disconnected till the supply is restored. If the recloser attempts to reclose, this time there is no reverse current contribution from the DG units. The use of reclosers does not solve the back-feed current directional problem. Moreover, it requires a specific logic scheme implemented in the FPI [10] and the feeder CB equipped with automatic recloser, which is not always the case.

Due to the enormous size of the Distribution Networks, the directionality of FPIs needs to be achieved with low-cost solutions. The replacement of the old, non-directional FPI by new, directional FPIs equipped with voltage sensors, working as directional relays, would imply an enormous investment by the DNOs. Voltage sensors are expensive and cannot be installed in life conductors. The installation requires the interruption of the power supply and is very time consuming because of the preparation of the cable termination. Moreover, most of the MV/LV cabins may not dispose of enough space to allocate them.

All these factors have motivated the FPI manufacturers to develop methods and solutions to avoid the usage of voltage sensors and, instead, use only low-cost current measurements and alternate signal processing techniques which are also suitable for directional detection. In section II, a review of voltage sensor-less techniques is provided, whereas section III develops a case study over a Belgian distribution feeder, belonging to the DNO Eandis. Some of the methods are implemented in order to illustrate the working principles under significant penetration of DG.

II. Directional Fault Detection Without Voltage Sensors

The directional techniques use only current inputs: phase and homopolar current measurements. The investigated techniques are found both in academic literature and industrial patent search and include a set of techniques of application either in directional relays or directional FPIs. Only those applicable to FPIs are described. These techniques have been classified in three categories, depending on the processed quantity.

A. Polarity of the phase current

Consider a grid like in Fig. 2, with a large DG unit located at the feeder end. The proposed method is directional for phase-to-ground and a phase-to-phase faults. Both the grid and the DG unit deliver current to feed the fault from both sides, in opposite directions. The same current with a change of direction, in phasor terms, is equivalent to shift it 180 degrees:

$$\underline{I}_{reverse} = 1\angle 180° \cdot \underline{I}_{forward} \tag{1}$$

Regarding the instantaneous values of such currents, the angle shift is equivalent to a change of polarity (different than polarization). Given a sudden current increase, the FPI detects the sign of the first half of the current waveform, the one with highest peak, as described in the standard IEC 60909 part-0 [11]. The indication of the sign of the first half of the current waveform is given by a green or a red LED or a LCD display.

In phase-to-phase faults, the currents in the faulted phases are equal in magnitude but with opposite directions, which means opposite polarity. Consider a MV/LV transformer cabin where 3 FPIs have been installed, one per conductor. The FPI of one faulted phase will trip the red LED indication whereas the other faulted phase, the green one, despite being in the same substation. The fault may be located by checking the last green flashing FPI and the first red one, evaluated on the same phase, as shown in Fig. 4 (b).

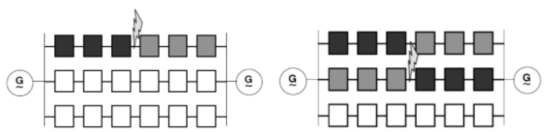

Figure 4: Directional fault detection method [12]. (a) Phase-to-ground fault. (b) Phase-to-phase fault.

The complete working principle of such directional FPI is detailed in the patent DE19756043 [13]. The good operation of such device is achieved as far as the first half wave of the current is the largest one. The performance of this method uncertainty in the directional detection when the current-voltage angle is 150 or 330 degrees. The detection of the fault still considers the classical over-current function (e.g. 200 A). This can be a problem when applying the method to isolated or compensated grounding systems.

B. *Symmetrical components*

The use of symmetrical components has been largely used to detect ground faults by sensing the homopolar current, for instance the cases shown in Fig. 5, but without providing directional indication. In this section, some methods have been proposed also in the field of directional relays.

Figure 5: Homopolar current FPI around the 3 cables, without shield [12]

1) *Ratio of sequences*

A sequence of publications propose several directional detection principles for distribution networks based on the use of ratios between different symmetrical components of the current. The first method was patented in EP1475874 [14], although the detailed simulations were exposed in [15]. The detection principle is to be applied in low impedance and resonant grounding systems and it is assumed a power factor of the total amount of connected loads greater than 0.8 ($\theta < 35°$), and the load angle is between [-55°,35°]. The study of this method is done over a grid with 2 HV/MV transformers in parallel, feeding 5 feeders. The proposed relay is allocated in different places in the grid: as an upstream bus-bar protection (secondary side of the transformer protection), as feeder protection and as closed loop protection.

The background of this method is the fact that during phase-to-ground faults, both the positive and negative sequence currents are very similar. Therefore, the considered ratio works with positive sequence of the pre-fault state and the negative sequence fault current. Moreover, the angle of the complex ratio is the parameter that determines the flow direction, that indicates reverse fault direction by

$$r = \arg\left(\underline{I}_2 / \underline{I}_{1,pre\text{-}fault} \right) \in [\pi/2+\theta \,;\, 3\pi/2+\theta] \quad (2)$$

In [16], simulations with several varying parameters were ran. The results show that this method works perfectly for phase-to-phase faults, but in case of phase-to-ground faults, some cases were reported with error. High rate of underground cables, very large or very low load conditions, high fault resistance ($R_{fault} > 50\Omega$) or grounding impedance above 600Ω were the reported causes.

The directional detection principle is expanded in [17], with the connection of DG to the grid, simulated in compensated and resistive grounding systems, but not in closed-loop feeders. The uncertainty of such algorithm is due to the lack of information about the grounding resistance and the inductance tuning, if compensated system, the load and DG powers, the capacitances of the grid. Therefore, it is found that a lot of information is required to increase the reliability. Moreover, the main problem when testing such algorithm is the amount of DG that is delivered to the loads downstream the generator, positive sequence current, which strongly influences the boundary between forward and reverse direction. The use of communications is proposed then, and it results in a successful detection principle, though non-directional.

The dependence of the positive sequence on the load flow conditions is tackled in [18], where two ratios are used for directional detection:

$$r = \arg\left(\underline{I}_2 / \underline{I}_0 \right) \quad (3)$$

Now, this parameter does not depend on the load flow, assuming balanced conditions and the zero-sequence is only found during phase-to-ground faults. The simulation results show good behavior in compensated grounding, despite in practice, CT phase measurement error lead to maloperation if the directional method is used as upstream protection. As feeder protection relays, the method is suitable. In resistive grounding system, uncertainty in the directional detection is found for low impedance values as upstream protection.

The second ratio proposed in [18], uses the ratio in the zero and the positive sequence currents for the fifth harmonic, instead of the fundamental 50 Hz frequency:

$$r = \arg\left(\underline{I}_{0,5th} / \underline{I}_{1,5th} \right) \quad (4)$$

This new approach may improve the performance of the directional relays as upstream protection, but the results do not improve significantly in compensated grounding systems for feeder protection. The calculation of the fifth harmonic increase, from pre-fault to fault, may improve the performance and provide adaptability to the grid conditions.

2) *Current polarization*

In the previous methods, the directional fault detection was tackled only for compensated and impedant grounding systems, whereas isolated grids were out of the scope. In [19], a directional relay is proposed for isolated grids under phase-to-ground faults. One of the main problems of this grounding system is that phase-to-ground faults do not provoke neither large phase over-currents nor zero-sequence over-currents. This makes the fault detection a difficult task, and the directional detection still more difficult. Herein, an isolated MV grid with 2 feeders was considered. It is found that during a phase-to-ground fault, the protective relays at each feeder head see the same zero-sequence current magnitude, but with opposite direction:

$$\underline{I}_{0,relay,feeder\text{-}1} = -\,\underline{I}_{0,relay,feeder\text{-}2} \quad (5)$$

This principle is extended with a sensitivity correction factor and the calculation of the integral of the product of the phase current by the zero-sequence current. The given indicator is then used to identify the faulted phase and the fault direction. The indicator is calculated every half cycle and therefore it provides fast detection. The method can be considered as a variant of the current polarization system. In this case, the polarizing quantity is the phase current and the operating quantity, the zero-sequence current. For each phase, a direction estimation is provided according to the formula of a digital phase comparator between two magnitudes *u* and *i*:

$$id = 2/m \cdot \sum_{k=m/4+1}^{3m/4} u(k+s) \cdot i(k) \Big/ UI \tag{6}$$

Where *id* is the indicator of direction, *m* is the number of samples within the basic period of the signals, *s* is the preset sensitivity of the relay, *u* and *i* are the signals to be compared and *U* and *I* are the rms values of the previous signals. Herein, the sign of the direction indicator of the three phases define a logic, based on comparisons such as greater or smaller than zero, that combine the three results to identify the faulted phase.

3) Correlation between zero-sequence and phase currents

A directional detection method for phase-to-ground faults in underground grids with high capacitive current is proposed in the patent EP1890165 [20] and expanded in [21]. It is mainly meant to be applied in compensated and impedant grounding systems. The proposed solution starts from the similitude between current waveforms during this fault type. During a forward phase-A to ground fault, the computed zero-sequence current will look like the faulted phase. In case of reverse fault, the zero-sequence current will look similar to the other two phases, as in Fig. 6.

In [20], the instantaneous phase current values are filtered, sampled and pre-processed. Later on, they are input in a trained Artificial Neural Network (ANN), which determines the direction of the fault. The method is of usefulness against the back-feed capacitive current. This method strongly depends on how the ANN is trained, and therefore an incorrect training leads to inappropriate coefficients which may lead to maloperation. Moreover, the application of one trained ANN in another grid may require a new training, thus becoming a costly operation.

In the patent EP2169799 [22], a variation of this method calculates the similarity between phase current and homopolar current using the Bravais-Pearson correlation index between signals (7).

$$r_{xy} = \left| \frac{\sum_{k=1}^{N}\left(x_k - \sum_{i=1}^{N} x_i \Big/ N\right) \times \left(y_k - \sum_{i=1}^{N} y_i \Big/ N\right)}{\sqrt{\sum_{k=1}^{N}\left(x_k - \sum_{i=1}^{N} x_i \Big/ N\right)^2 \times \left(y_k - \sum_{i=1}^{N} y_i \Big/ N\right)^2}} \right| \tag{7}$$

If the fault is forward, the correlation factor will be close to 1. Hence, from the correlation factors, the mean μ and the standard deviation σ are obtained and the forward direction is given by (8), though other formulas are also proposed in [22].

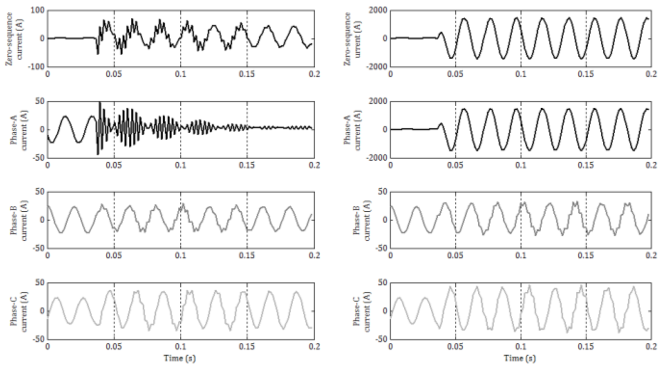

Figure 6: Similarity between current waveforms. Left: reverse phase-A to ground fault. The zero-sequence looks like a mix of phase-B and C currents. Right: forward phase-A to ground fault. The zero-sequence currents looks alike to phase-A current.

$$\sqrt{3} \cdot \sigma + \mu > 1 \tag{8}$$

Lots of simulations were done in grids with different grounding systems and fault locations in order to evaluate the performance of the method. In general, the method performs well for all the grounding system with the exception of isolated neutral grids, where upstream, reverse faults are sometimes detected as forward faults [23].

4) Comparison of rms-values

Also in EP2169799 [22], an alternative procedure to determine the direction of the fault is described. The second method consists of calculating the rms values of each phase current and compare them with the average rms value, calculated from the three phases. The comparison for the phase-A FPI would be done as

$$P_A = \mathrm{I}_{\mathrm{rms,A}} \, / \, \mathrm{average}\{\mathrm{I}_{\mathrm{rms,A}};\ \mathrm{I}_{\mathrm{rms,B}};\ \mathrm{I}_{\mathrm{rms,C}}\} \tag{9}$$

The criterion to detect the direction is such that if P_A is greater than 1, the direction is forward. The same comparison is to be done for the other phases. This method is only intended to be used for phase-to-ground fault directional detection.

5) High-frequency cable discharge

In the patent EP2421110 [24], another method to detect phase-to-ground faults is proposed. The input of such method is the homopolar current measured by means of a unique current sensor around the three conductors. The detection principle is the classical zero-sequence over-current, whereas the directional principle is the detection of the high-frequency of the cable discharge, the resonance of the capacitances and inductances of the cable sections beyond the fault, as shown is (10). The algorithm counts the number of zero crossings of the zero-sequence current (*N*) and the crossing of its time derivative (*di₀/dt*) after the fault is produced, *dN*. If *N* or *dN* are larger than a threshold, it is assumed a reverse fault, otherwise, it is detected as forward fault.

$$f_{discharge} = 1 \Big/ 2\pi\sqrt{L_1 C_0} \tag{10}$$

The patent text makes explicit the use of a high sampling frequency up to 20 kHz. This frequency may be high enough to detect the transient discharges.

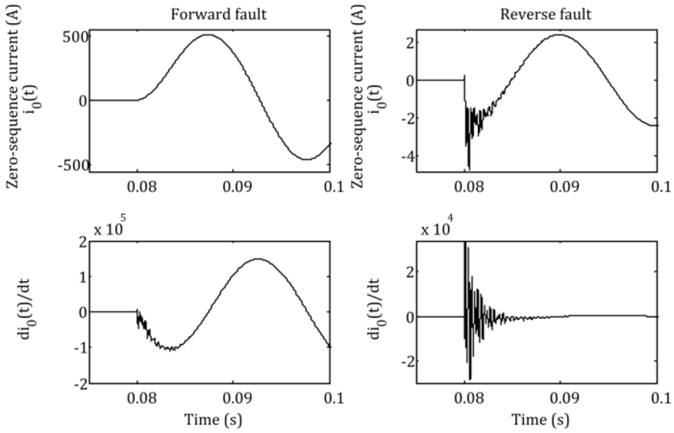

Figure 7: Detail of the zero-sequence current and the *di0/dt* sensed by 2 FPIs at each side of a fault. Left: forward fault (no zero-crossings). Right: reverse fault (large amount of crossings in *di0/dt* due to the frequency discharge).

The high-frequency cable discharge method is intended to be applied for ground fault directional detection.

6) Pseudo-homopolar current frequency signature

The previous methods were exclusively designed to detect phase-to-ground faults and, consequently, they are of no application for other fault types. The patent EP2383856 [25] provides a complete set of conditions to distinguish between all fault types and directions. The patent introduces the concept of frequency signature of the pseudo-homopolar current. The pseudo-homopolar current is calculated from the positive sign phase currents, according to:

$$\underline{I}_{0p} = \underline{I}_A^+ + \underline{I}_B^+ + \underline{I}_C^+ \tag{11}$$

The frequency signature consists of the frequency spectrum of such signal, from where the dc, the 50 Hz and the 100 Hz components amplitude is analyzed. The method is able to distinguish all the fault types if complemented with the second implementation of II.B.4 (comparison of the rms values between phases). Both methods, combined, provide a way to identify the fault type and the direction. In practice, a logic algorithm has been implemented that after evaluating a set of conditions in a specific order provide the fault identification.

A major advantage of this method is that it does not require pre-defined thresholds, and therefore it is called auto-adaptive Fault Passage Indicator [23].

C. Phase angle shift

Another voltage sensorless directional detection method is proposed in the patent EP2278676 as a fault direction indicator [27], developed further as directional over-current relay, in [28] and [29]. The directional detection principle is taken from [30], and it is based on a circuit like Fig. 8.

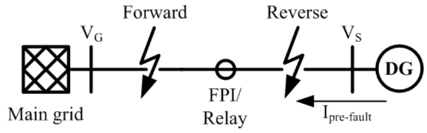

Figure 8: Simplified circuit for directional detection studies

Note the direction convention concerning forward and reverse faults and that the pre-fault current is considered to flow from the DG source in the direction of the grid and is sensed by the FPI ($\underline{I}_{pre\text{-}fault}$):

$$\underline{I}_{pre\text{-}fault} = (\underline{V}_S - \underline{V}_G) / \underline{Z}_{SG} \tag{12}$$

The sensed current in fault conditions is calculated for both fault locations, reverse and forward. $\underline{Z}_{SF}$ and $\underline{Z}_{GF}$ are the impedances from the DG source to the fault, in forward fault conditions, and from the grid to the fault, for reverse faults, respectively.

$$\underline{I}_{forward} = \underline{V}_S \ / \underline{Z}_{SF} \tag{13}$$

$$\underline{I}_{reverse} = \underline{V}_G \ / \underline{Z}_{GF} \tag{14}$$

Consequently, the current increase seen by the FPI, from pre-fault to fault conditions is:

$$\underline{I}_R = \underline{I}_{pre\text{-}fault} - \underline{I}_{reverse} = \underline{I}_{pre\text{-}fault} - \underline{V}_G \ / \underline{Z}_{GF} \tag{15}$$

$$\underline{I}_F = \underline{I}_{pre\text{-}fault} + \underline{I}_{forward} = \underline{I}_{pre\text{-}fault} + \underline{V}_S \ / \underline{Z}_{SF} \tag{16}$$

Note the sign difference between forward and reverse current increases, which leads to a phasor diagram as:

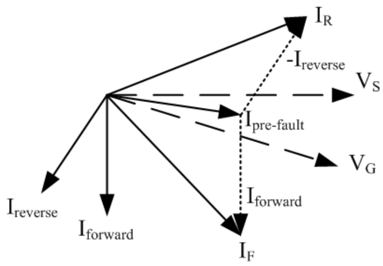

Figure 9: Phasor diagram for directional detection

It is assumed that the phase angle change does not change significantly during normal load conditions, however, it is sensed continuously every cycle, so that in fault conditions the angle change can be detected. In the patent [27], an exhaustive list of possible methods to implement the detection algorithm is provided. This classification includes the following categories: min-max logic, comparator logic, sign logic, frequency analysis decision, black-box models, mathematical models and fuzzy logic. Herein, it is also proposed the use of this method with different magnitudes, e.g. current phasors, symmetrical components, amongst many other possibilities. This method will be further implemented with the positive sequence phasor.

In [28] and [29], the implementation down to the signal processing level is described, as well as the limitations found for the detection algorithm: (i) the direction estimation is estimated based on the pre-fault current. If the pre-fault direction current changes, the criteria to distinguish forward and reverse faults inverts, and the algorithm would not be able to determine the direction; (ii) it is necessary to detect valid pre-fault current, in order to provide relative direction indication; (iii) given that the algorithm detects the phase change cycle per cycle, depending on the sampling frequency, there will be a minimum angle detection per sample, (iv) frequency deviations, inherent unbalances in the system, noise and other measurement uncertainties may influence the accuracy of the phasor computation.

Despite the above-mentioned limitations, the proposed method is described as fast, with a directional detection in about 7 ms and immune to high fault resistance cases.

III. APPLICATION CASE

The case study has been developed over a feeder from the Belgian operator Eandis. The DNO operates a grid with low resistive-inductive impedance grounding system and almost exclusively underground cables. The grounding impedance is sized to provide 2kA in phase-to-ground faults, whereas phase-to-phase faults lead to a maximum phase current of 20 kA.

The selected 12 kV-feeder is representative of the Belgian operator with a purely open-ring topology, without laterals. The feeder has a normally open switch in the middle of the loop, which is eventually closed for service restoration purposes. For the actual case study, in normal operation, one half of the feeder is taken for simulation. In urban grids, the average length between substations is about 400 m. The secondary substations are modeled as loads, corrected by a use-factor and with a cos(phi) = 0.9 inductive, phi = 25,84 degrees.

For the current simulations, it is assumed that the FPIs are located according to the standard IEEE 1610-2007: one FPI over each outgoing cable of the substation. One fault location has been simulated: in the middle of the feeder. This allows to evaluate the performance of the directional sensor-less FPIs at each side of the fault, allocated as shown in Fig. 10.

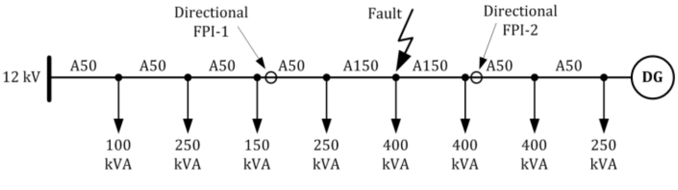

Figure 10: Representative MV Belgian feeder for study

TABLE I. CABLE PARAMETERS

	R_1	**X_1**	**C_1**	**R_0**	**X_0**	**C_0**
Cable type	(Ω/km)	(Ω/km)	(μF/km)	(Ω/km)	(Ω/km)	(μF/km)
Al-50mm2	0,641	0,129	0,23	1,4743	1,584	0,13
Al-150mm2	0,206	0,108	0,28	0,761259	0,77	0,28

A single DG unit has been connected at the very end of the feeder. The size of the DG has been increased significantly. Different fault types are created. The implemented methods are the polarity (II.A), correlation (II.B.3) and the current angle shift (II.C). The results depend strongly on the way the methods are implemented, but they give good approximation of the performance over the case-study grid.

The simulations have been ran with different sampling frequencies to match the requirements of the algorithm. The method of current polarity is in reality implemented with analog electronics, however, to illustrate the performance, the same operation principle has been implemented digitally.

1) Polarity of the phase current

Phase-to-ground faults produce a forward current large enough to be detected by FPI-1. Despite the DG unit provides some reverse current, it is too small (< 200 A) to be sensed by FPI-2. Hence, the fault is only indicated by the FPIs upstream the fault.

During a poly-phase fault, both FPIs at each side of the fault may sense the over-current. When checking the FPIs status, they have to be compared phase by phase. In Fig. 11 it is plotted the polarity of the instantaneous current during a phase-A to phase-B fault, with a DG unit of 5 MVA.

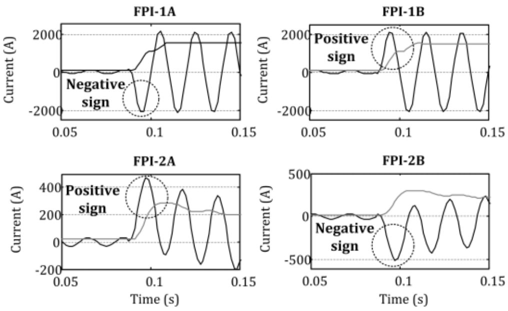

Figure 11: Phase-A to phase-B fault, polarity of the first half wave. Left: FPI-1A and FPI-2A. Right: FPI-1B and FPI-2B. Note that both FPIs in the same phase point to the fault in between, by indicating different polarity (sign).

No mal-indication case has been found while increasing the size of the DG from 100 kVA till 5 MVA. The fault inception angle determines the polarity, giving different polarity for the same fault if it is produced half a period later (α versus α+T/2).

2) Correlation between zero-sequence and phase currents

This method is to be applied to detect phase-to-ground faults. Fig. 12 shows the absolute value of the Bravais-Pearson correlation coefficient in time, between the phase currents and the homopolar current. The following figures (Fig. 12, 13 and 14) refer to the scenario where 5 MVA of DG were connected.

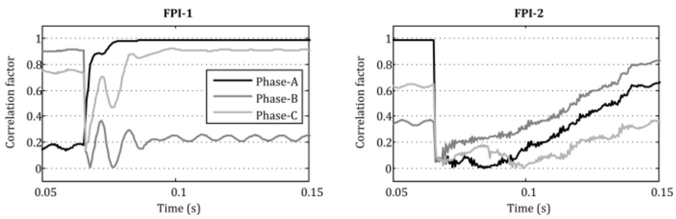

Figure 12: Correlation factors over time. Note that the correlation factor of FPI-1 in phase-A are very close to 1.

The mean and the variance are calculated for each FPI, at every time step, with $r_{A,t}$, $r_{B,t}$ and $r_{C,t}$.

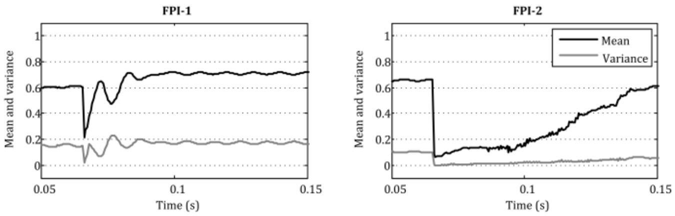

Figure 13: Mean and variance from the correlation coefficients. Note that FPI-1 adopts relatively high values of mean (> 0,5), as specified in [22].

Finally, the criterion to determine the direction is given by (8), the parameter and consists of an inequality that divides the forward and the reverse regions.

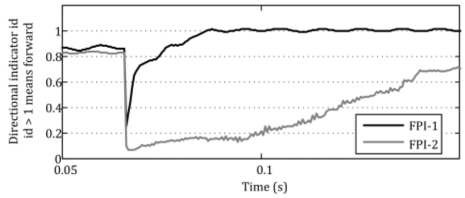

Figure 14: Directional indicator for both FPIs. Note that FPI-1 is slightly above 1 (forward) and FPI-2 is clearly below 1 (reverse).

The criterion for forward/reverse detection has been ran for different penetration levels, giving accurate results. Although the method has performed well in all the simulated cases, the directional indicator is more distinguishable for low penetration levels.

3) Phase angle shift

The phase angle shift method has been implemented with the positive sequence current phasor and it has been tested for different fault types while increasing the size of the DG unit.

TABLE II. POSITIVE SEQUENCE ANGLE SHIFT PER FPI (DEGREES)[a]

Fault type	DG [MVA]	FPI-1	FPI-2
PTG (A-G)	1	-14,9	7,2
	2	-15,4	13,8
	3	-15,8	20,2
	4	-16,3	25,9
	5	-16,7	30,5
PTP (A-B)	1	-10,9	75,2
	2	-12,5	89,9
	3	-13,9	92,0
	4	-15,4	90,8
	5	-16,7	88,2
PTPTG (A-B-G)	1	-11,4	77,0
	2	-12,9	90,5
	3	-14,4	92,2
	4	-15,8	90,8
	5	-17,1	88,2
3P (A-B-C)	1	-11,4	110,6
	2	-13,0	106,6
	3	-14,5	102,5
	4	-16,0	98,2
	5	-17,4	93,9

a. Negative sign: forward direction
Positive sign: reverse direction

From Table II it can be seen that FPI-1 sees a negative sign phase angle shift, which means forward direction, whereas FPI-2 sees positive shift, reverse direction, according to the principles previously exposed.

IV. CONCLUSIONS

The use of directional Fault Passage Indicators is expected to increase in the near future. Two factors may speed up the need for these devices: the back-feed capacitive current due to the Distribution Network expansion and the bidirectional power flows due to the penetration of DG units.

The literature review in the field shows that, up to date, there has been, and is still ongoing, research on this field. Big manufacturers have come up with innovative solutions brought into market to satisfy the needs of “low-cost” directionality for the DNOs. Some of these solutions were conceived initially as protective relays, becoming later on directional FPIs: both devices can incur the same directional problems. The simulations show that for low DG penetration, directionality might not be an issue, because the feeder-end DG fault contribution is too small to trip the FPIs. However, towards the scenario of large DG penetration, directionality becomes definitively a problem.

From the literature review, it can be seen that all the investigated methods show limitations of different nature in their directional detection principle. However, towards the application of such methods in the grid, two aspects need to be considered: the grid grounding system and the fault type that the FPI can detect directionally. Some methods offer the possibility of covering all the fault types, but limited to specific grounding systems, whereas other methods provide directionality for all grounding systems, but only for specific fault types.

Some algorithms have not been described in this paper, such as wavelets, expert systems, amongst other algorithms, which, in general, may require a specific training data set or the knowledge of the grid topology, which might not be feasible in practice. Some current-based algorithms have been found in literature to work as directional relays, but not as FPIs, hence not described in the paper. Most of these directional voltage sensor-less FPIs use rather “non-conventional” techniques, but very accurate performance in the way they are implemented. Some of the directional methods described in the paper may be complemented with the over-current detection function. The case-study illustrates the underlying principles over the particular Belgian feeder.

Although directional FPIs without voltage sensors are a short or mid-term solution, the use of voltage sensors may be an attractive option for the DNOs, since it may allow other capabilities to their equipment, such as monitoring or voltage control strategies, amongst many other. One of the challenges up-to-date is the concept of self-healing grids, which can re-configure the grid topology in case of outage. This can only be done through more automation in the grids. The appropriate performance of the directional FPIs is posed in doubt under this assumption.

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REFERENCES

[1] Cooper Power Systems, "Faulted circuit indicator application guide," Waukesha, US, October 1998.

[2] D. J. Krajnak, "Faulted circuit indicators and system reliability," in IEEE Rural Electric Power Conference, 2000, 1-4.

[3] H. Falaghi, M. R. Haghifam, M. R. Osouli Tabrizi, "Fault indicators effects on distribution reliability indices," in 18th International Conference on Electricity Distribution, CIRED, Turin 2005.

[4] E. Vidyagasar, P. V. N. Prasad, A. Ather Fatima, "Reliability improvement of a radial feeder using multiple fault passage indicators," in Energy Procedia, 2nd International Conference on Advances in Energy Engineering (ICAEE 2011).

[5] M. Jarrega-Dominguez, "News in fault passage indicators in overhead and underground MV lines," in 17th International Conference on Electricity Distribution, CIRED, Barcelona 2003.

[6] F. M. Angerer, "New developments in faulted circuit indicators help utilities reduce cost and improve service," in IEEE Conference papers, Paper No 08 B4, 2008.

[7] J. Roberts, A. Guzman, "Directional Element Design and Evaluation". Schweitzer Engineering Laboratories, Inc., 2006, technical report.

[8] J. Horak, "Directional Overcurrent Relaying (67) Concepts," in 59th Annual Conference for Protective Relay Engineers, 2006. IEEE, 2006, 164-176.

[9] IEEE standard 1610-2007, "IEEE Guide for the Application of Faulted Circuit Indicators for 200/600 A, Three-phase Underground Distribution", 2008.

[10] C. Gonzalez-de Miguel, T. De Rybel, J. Driesen, "Implementation of a digital directional fault passage indicator," unpublished. Accepted for the 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013.

[11] IEC standard 60909, part-0, "Short-circuit currents in three-phase ac systems. Part-0: calculation of currents", 2002.

[12] Horstmann GmbH, "Short-circuit indicators and earth-fault indicators," Heiligenhaus, Germany, 2011.

[13] H. Horstmann, "Detecting short circuit in cable network of electrical power supply system," Dipl.-Ing. H. Horstmann GmbH, German patent DE 19756043, Heiligenhaus, Germany, 1999.

[14] P. Bertrand, X. Le Pivert, "Device and method for detecting an earth fault and relay with such a device," European patent EP 1475874, Schneider Electric Industries SAS, Rueil-Malmaison, France, 2004.

[15] X. Le Pivert, P. Bastard, I. Gal, "How symmetrical components may help to suppress voltage sensors in directional relays for distribution networks," in 17th International Conference on Electricity Distribution, CIRED, Barcelona 2003.

[16] M. Petit, X. Le Pivert, P. Bastard, I. Gal, "Symmetrical components to suppress voltage sensors in directional relays for distribution networks: effect of distributed generation," in 8th IEE International Conference on Developments in Power System Protection, 2004, vol. II, 575-578.

[17] M. Petit, P. Bastard, X. Le Pivert, C. Poulain, "Directional relays without voltage sensors for distribution networks: use of symmetrical components and effect of the distributed generation," in 18th International Conference on Electricity Distribution, CIRED, Turin 2005.

[18] M. Petit, X. Le Pivert, L. Garcia-Santander, "Directional relays without voltage sensors for distribution networks with distributed generation: Use of symmetrical components," in Electric Power Systems Research 80, 1222-1228, 2010.

[19] Z. N. Stojanović, M. B. Djurić, "An algorithm for directional earth-fault relay with no voltage inputs," in Electric Power Systems Research 96, 144-149, 2013.

[20] P. Bastard, B. Gotzig, "Method of directional detection of a fault in the ground connection and device for implementing the same," European patent EP 1890165, Schneider Electric Industries SAS, Rueil-Malmaison, France, 2007.

[21] P. Bertrand, R. Kaczmarek, X. Le Pivert, P. Bastard, "Earth-fault detection in a compensated earthed network, without any voltage measurement: a new protection principle," in 16th International Conference on Electricity Distribution, CIRED, Amsterdam 2001.

[22] G. Verneau, P. Cumunel, "Directional detection of a ground fault," European patent EP2169799, Schneider Electric Industries SAS, Rueil-Malmaison, France, 2009.

[23] G. Verneau, Y. Chollot, P. Cumunel, "Auto-adaptive fault passage indicator with remote communication improves network availability," in 21st International Conference on Electricity Distribution, CIRED, Frankfurt 2011.

[24] G. Verneau, "Directional detection of an earth fault with a single sensor," European patent EP2421110, Schneider Electric Industries SAS, Rueil-Malmaison, France, 2011.

[25] P. Cumunel, G. Verneau, "Identification and directional detection of a defect in a three-phase network," European patent EP2383856, Schneider Electric Industries SAS, Rueil-Malmaison, France, 2011.

[26] G. Verneau, Y. Chollot, P. Cumunel, "Improving network availability with intelligent electronic devices," Schneider Electric, 2011.

[27] B. Deck, A. Ukil, "Fault direction indicator device and related methods," European patent EP 2278676, ABB Technology AG, Zürich, Switzerland, 2009.

[28] A. Ukil, B. Deck, V. H. Shah, "Smart distribution protection using current-only directional overcurrent relay," in Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES.

[29] A. Ukil, B. Deck, V. H. Shah, "Current-only directional overcurrent relay," in IEEE Sensors Journal, Vol. XI, No. 6, 2011.

[30] M. M. Eissa, "Evaluation of a new current directional protection technique using field data," in IEEE Transactions on Power Delivery, Vol. 20, No. 2, 566-572, 2005.

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